3. Catchment Hydrology

3.1 Hydrological modelling systems

The main components of a hydrological model are summarised in fig.3.1 (Cornell University, 2003). Rainfall reaching the ground may enter the soil by *infiltration*, or may flow down the hillslope as *surface runoff*. Surface water can return to the atmosphere by *evaporation*. Water within the root zone may be taken up by plants and subsequently released into the atmosphere by *transpiration* from the plant leaves. Water within the soil may produce *lateral flow* downslope at shallow depth, or may percolate downwards to *groundwater store*. Water may also be drawn upwards from the subsoil by *capillary action* if the topsoil becomes dry. Surface runoff and shallow lateral flow may enter streams fairly quickly after the start of a storm event. Groundwater may be released to streams more slowly and over a longer period as *baseflow*. Once water has entered streams, it will be *routed* downstream.

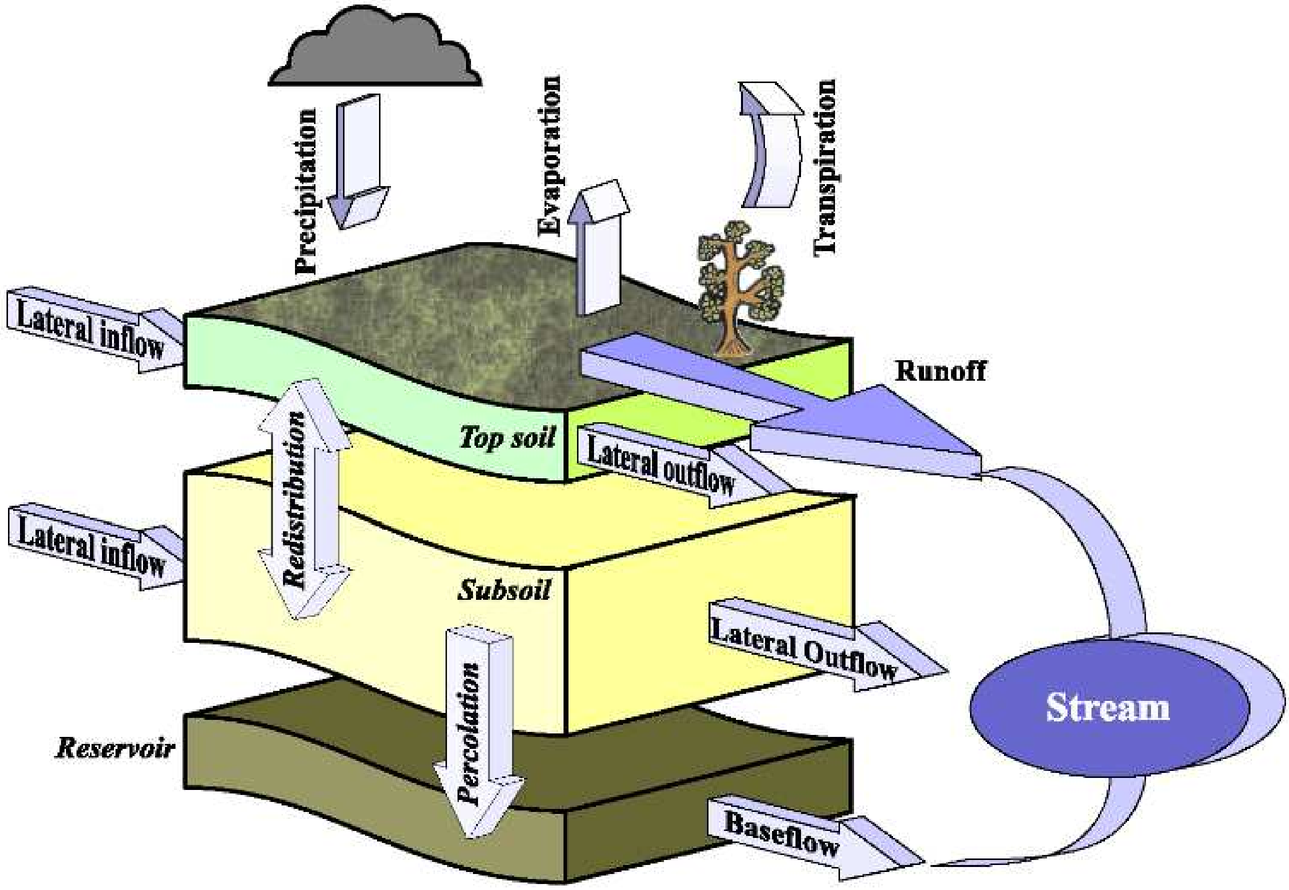


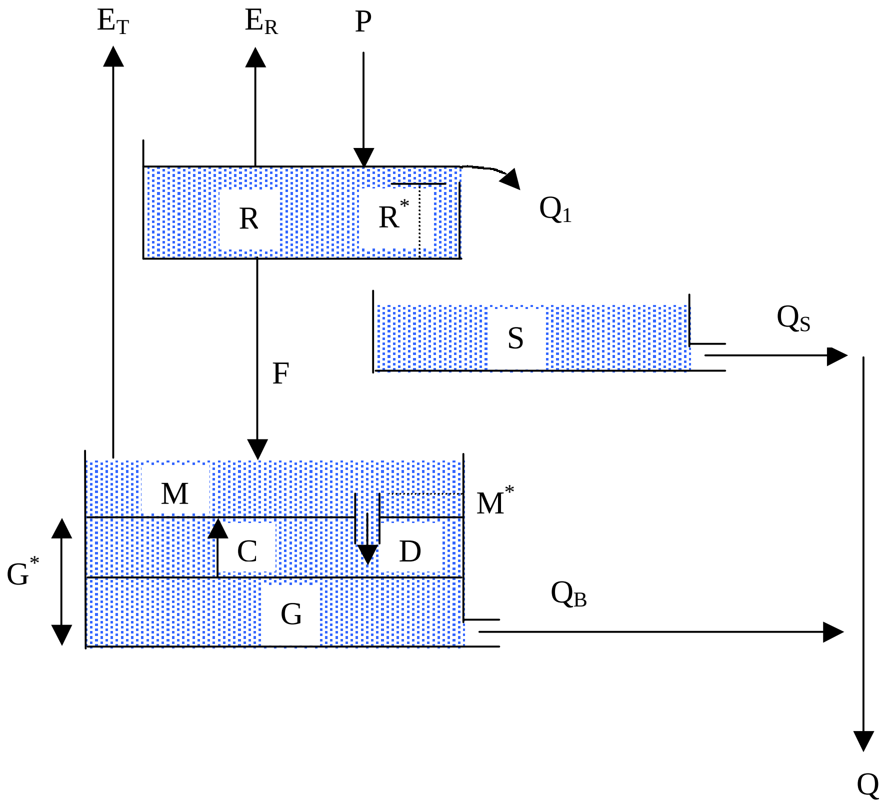
Figure 3.1: Main components of a hydrological model (Cornell University, 2003)

The conceptual model described above was first formulated mathematically in the 1960's as the Stanford Watershed Model. This system uses a series of water stores, with the rates of inflow and outflow to individual stores controlled by parameters representing physical properties of the hillslope environment. The system is illustrated in fig.3.2 (after Dawdy and O'Donnell, 1965).

Components of the Stanford Watershed Model may be divided into:

- precipitation input, generally representing the rainfall distribution across the catchment in space and time,
- volumes of water within the surface, soil, groundwater and river routing stores at any particular time, which may be controlled by soil depth and porosity,
- parameters controlling the rate at which water can pass between the different stores, which will be dependent on the hydrological properties of the soil and bedrock,
- parameters determining the rate of water loss through evaporation and transpiration, which will be determined by the nature of the ground surface and vegetation, and also by the prevailing climatic conditions,
- parameters determining the rate at which water released into rivers will be routed downstream through the river system.

Whilst the Stanford Model provides a good theoretical basis for hydrological modelling, a number of assumptions must be made in order to generate a workable computer simulation of a real watershed. The simplest approach is to assume that rainfall input and hydrological parameters are approximately uniform across the catchment, so that average catchment values can be used in the modelling equations. This leads to *lumped parameter models*, of which the Institute of Hydrology HYRROM model (fig.3.3) is an example.



C	maximum rate of capillary rise
D	recharge to groundwater store
E_R	evaporation from surface water store
E_T	evapotranspiration from soil water store
F	infiltration to soil moisture store (parameters f_0,f_c,k)
G	groundwater store (parameter K_g)
G^*	groundwater storage threshold
M	soil moisture store
M^*	soil moisture storage threshold
P	precipitation input
Q	total stream discharge
Q_1	surface runoff
Q_B	outflow from groundwater store
Q_S	outflow from surface water routing store
R	surface water store
R^*	surface water storage threshold
S	surface water routing store (parameter K_S)

Figure 3.2. Stanford Watershed Model (after Dawdy and O’Donnell, 1965)

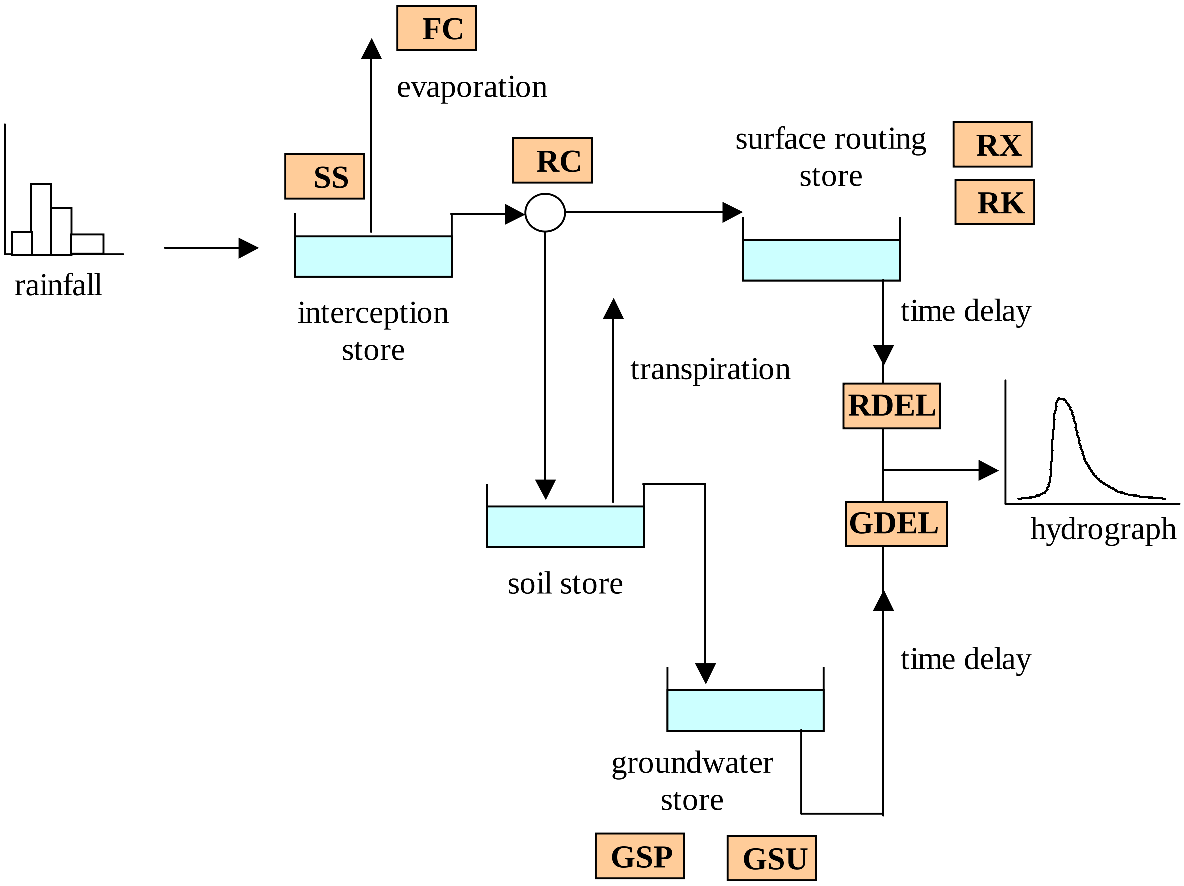


Figure 3.3: HYRROM model using nine parameters, identified by codes in the diagram above, to control the rates of input, output and transfer of water between the stores. (after Institute of Hydrology, 1988)

The lumped parameter approach can be very effective in predicting hydrograph responses at the output of a catchment. Although it may be difficult or impossible to accurately measure the required model parameters in the field, these can be optimised automatically by training the program with historical data. Parameters are adjusted to produce a best fit between the model output and real hydrographs recorded for the river.

The lumped parameter approach does, however, have some serious disadvantages:

- In a catchment of complex geology and varied vegetation, the assumption that parameters can be represented by average catchment values may not be valid.

- Reliance is often placed on automatic calibration of parameters. Optimisation algorithms work by systematically adjusting parameters in a direction which moves towards a lower overall error value, often the root mean square difference between the true and simulated hydrographs. It is possible that quite different sets of parameter values will produce an equally good optimisation. This situation is termed *equifinality*. An example is given in fig.3.4 for the simple case of two parameters, where combinations of the values A_1, B_1 and A_2, B_2 may represent similar minimums on a contoured error surface.

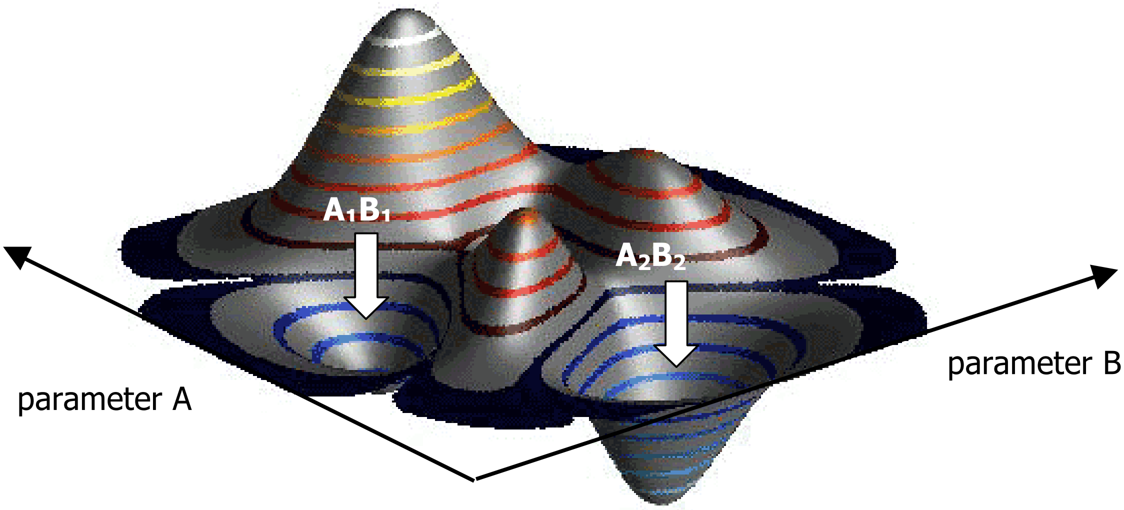


Figure 3.4: Two possible runs of an optimisation algorithm leading to different minima on the error surface

Equifinality may not be a problem if the prediction of river discharge is the sole objective of the model. There must be serious doubt, however, as to whether the parameter values chosen represent any true physical properties of the catchment.

- Lumped parameter models generally work well when predicting river discharges within the interpolation range of the data used for parameter calibration. Results may, however, become increasingly inaccurate when extrapolating beyond the known data to predict hydrographs for extreme storm events.

For these reasons and the considerations given below, a lumped parameter approach is considered unsuitable for meeting the objectives of the Mawddach research project:

- Wide variations in rainfall, geology, soils and vegetation are known to occur on a kilometre scale, so averaging of parameters across large areas is not appropriate.
- An objective of the research is to predict changes in river flows in response to changes in land management, so a clear link between model parameters and measurable catchment characteristics is necessary.
- A good understanding of the mathematical linkage between parameters measured in the field and model output should allow increased confidence in prediction beyond the limits of the historical records. This may be important for estimating the possible effects of a changing rainfall regime in future years.

An alternative mathematical approach which relates more closely to the physical characteristics of the catchment is the TOPMODEL concept of Bevan (1997). This makes use of the Kirkby topographic index γ:

$$\gamma = \frac{a}{\tan \beta}$$

where a is the land surface area draining to a unit contour length on the hillslope, and β is the slope angle at that point (fig.3.5).

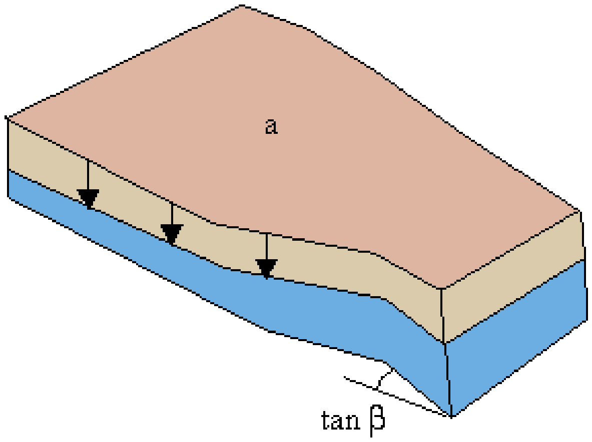


Figure 3.5: Determination of the Kirkby topographic index
(after Bevan, 2001)

A high value of topographic index represents a likelihood of saturated conditions, and occurs when a large upslope area drains onto gently sloping ground. By contrast, a low value of topographic index represents the likelihood of dry conditions, and may result from a small upslope area draining onto a steep slope. Areas of hillslope with similar values of topographic index would therefore be expected to behave similarly hydrologically. An advantage of the TOPMODEL approach is that the topographic index is an entirely geometrical concept, so can be computed automatically from a digital elevation model of the ground surface.

TOPMODEL makes a simplifying assumption that downslope hydraulic transmissivity T at any point on a hillslope can be expressed as a function of the water storage deficit at that point, measured as the depth to the water table.

$$T = T_0 e^{-D/m}$$

where T_0 is the lateral transmissivity when the soil is just saturated, D is the local depth to the saturated soil level, and m is a parameter controlling the rate of increase in transmissivity. With this assumption, the downslope saturated subsurface flow rate Q per unit contour length is given by:

$$Q = T_0 \tan \beta \exp\left(- D/m\right)$$

The saturated transmissivity parameter may be varied across the catchment to represent variations in soil type.

An alternative modelling approach is to subdivide the catchment into zones which might be expected to behave in a hydrologically similar manner. These zones are termed *hydrological response units*. Calculations of water storage and outflow are then carried out separately for each unit, with the outflow being routed to the next unit downslope or downstream. A hydrological response unit is likely to require:

- a relatively uniform slope angle, so that a representative value for downslope flow can be computed,
- relatively uniform soil and bedrock characteristics, so that representative values for hydraulic conductivity can be determined,
- relatively uniform surface characteristics and vegetation, so that representative values can be determined for evaporation and transpiration.

A model using hydrological response units is HEC-1, available within the Watershed Modelling System package (Goldman and Ely, 1990). HEC-1 has also been used in experiments for the Mawddach basin and will be discussed in detail in section 3.2.

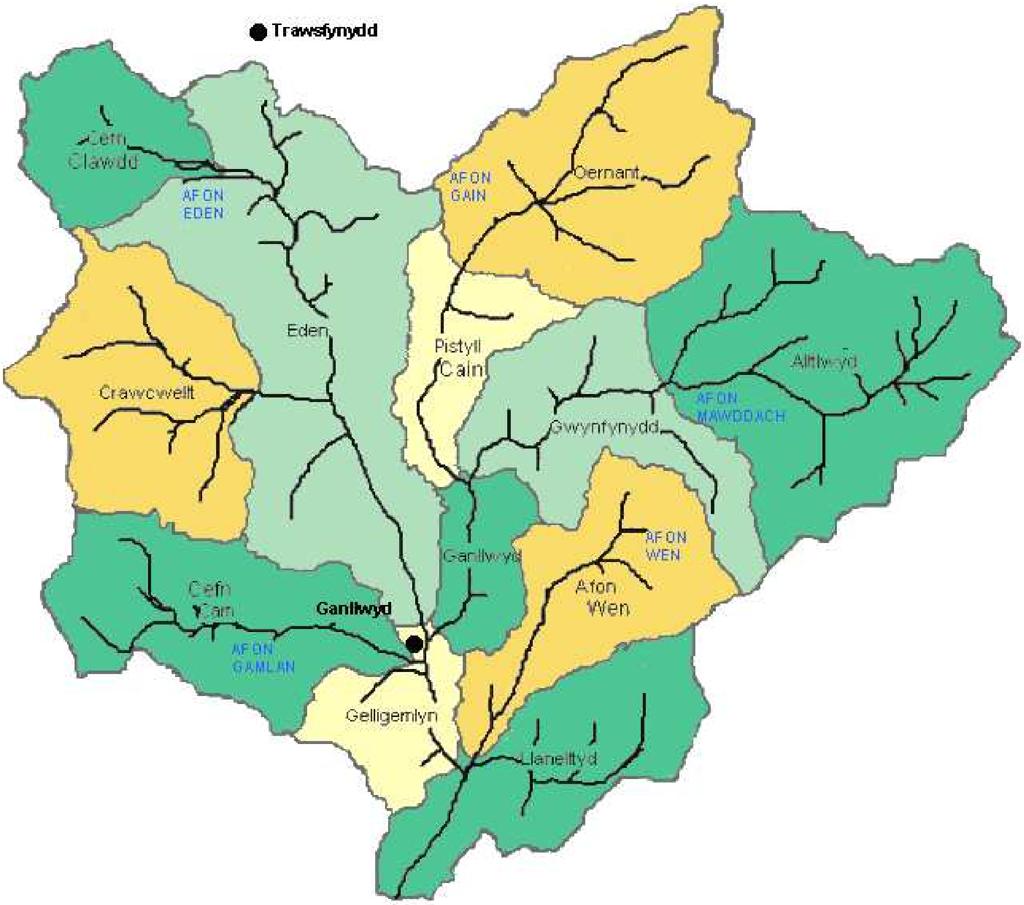


Figure 3.6: HEC-1 model for the Mawddach sub-catchments

HEC-1 requires the study area to be divided into sub-catchments (fig.3.6) which can be treated as having uniform properties of slope, soil runoff and infiltration characteristics. Additional sub-catchments can be defined as necessary, until the assumption of approximately uniform hydrological response units is achieved.

Within the HEC-1 package, several different methods of determining soil infiltration rate in response to rainfall are available. An option which has been employed in the Mawddach modelling is the US Soil Conservation Service curve numbers method (fig.3.7). This allocates a parameter on the basis of soil type and vegetation, which can then be used in the calculation of runoff generation.

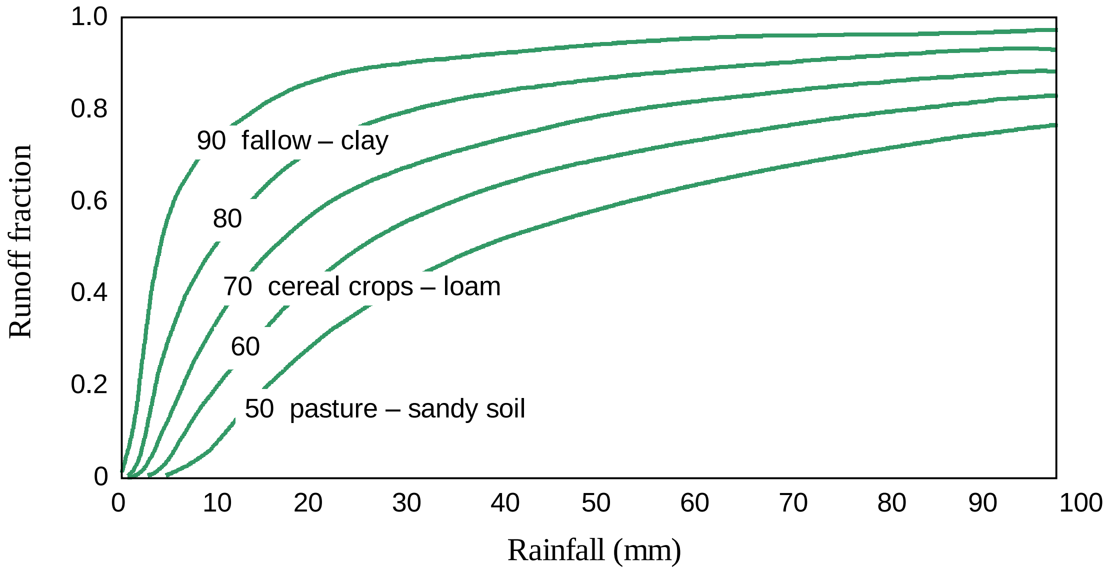


Figure 3.7: SCS curve number plots (after Bevan, 2001)

HEC-1 makes use of the kinematic wave equation for modelling the downslope flow of surface runoff:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = r$$

where:

$\frac{\partial A}{\partial t}$ is the rate of change of water depth on the hillslope surface,

$\frac{\partial Q}{\partial x}$ is the variation in discharge with distance down the hillslope,

r is water gained or lost per unit area.

The kinematic wave equation can be combined with Manning's equation:

$$Q = \frac{1.486}{n} A R^{2/3} S^{1/2}$$

which determines discharge Q in terms of slope S, hydraulic radius R, cross sectional area of the flow A, and a roughness factor n. This equation can be written in a simplified form by combining variables to give:

$$Q = \alpha A^{m}$$

where α and m are parameters related to flow geometry and surface roughness. This leads to the equation:

$$\frac{\partial A}{\partial t} + \alpha m A^{(m-1)} \frac{\partial A}{\partial x} = r$$

This equation can be solved to determine water movement down a hillslope over time, as a function of surface roughness and slope angle.

HEC-1 works well in simulating hydrographs from historical storm events, and meets the desired criterion of having parameters which link directly to measurable characteristics of the catchment. However, it is limited to the modelling of a single storm. Infiltration to the groundwater store is treated as a loss from the model, so long term base flow into rivers is not represented. This difficulty is illustrated in fig.3.8, which compares the recorded and simulated hydrographs at Tyddyn Gwladys on the River Mawddach for the July 3, 2001, flood event.

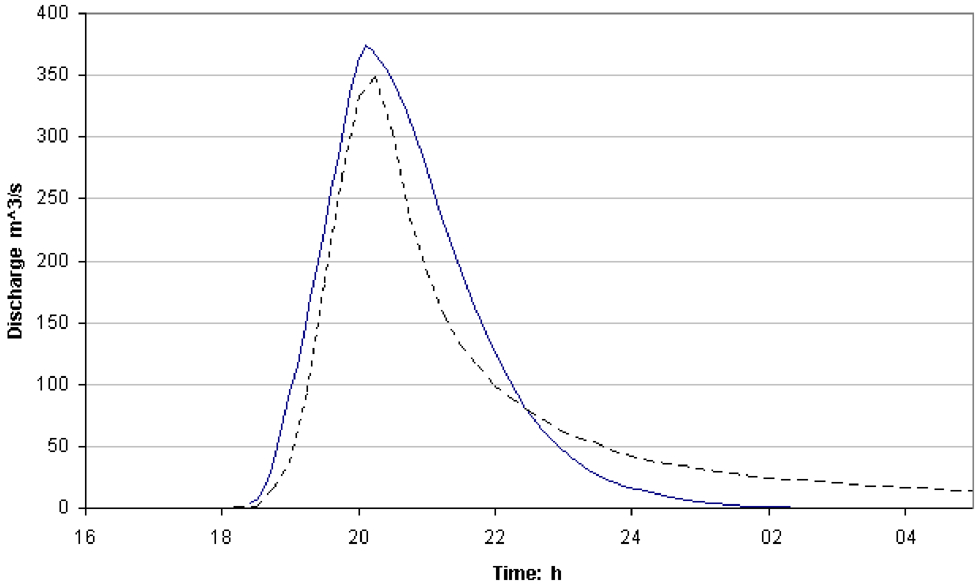


Figure 3.8: Synthetic hydrographs (solid line) and observed hydrograph (dotted line) for the July 3, 2001, flood event, Tyddyn Gwladys.

There is good agreement for the peak of the flood when hillslope runoff is the main contribution to the river flow. However, slower release of groundwater over the subsequent 12 – 24 hours is not represented by the model. The inability to handle groundwater flows adequately prevents HEC-1 being used in long term studies of the effects of antecedent conditions on flood generation.

A number of hydrological models have been developed which combine hillslope runoff simulation with groundwater baseflow. An alternative approach is to handle groundwater processes with a separate groundwater model MODFLOW (McDonald and Harbaugh, 1988) within the Groundwater Modelling System package.

The mathematical basis for MODFLOW is Darcy's equation for the flow of water through a porous medium (fig.3.9):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W = S\,\frac{\partial h}{\partial t}$$

where K_x is hydraulic conductivity in the x-direction,

$\frac{\partial h}{\partial x}$ is the gradient of hydraulic head in the x-direction,

$\frac{\partial h}{\partial t}$ is the change in hydraulic head with time,

S is the water storage capacity of the porous medium, and

W represents water added as input, or lost as output from the system:

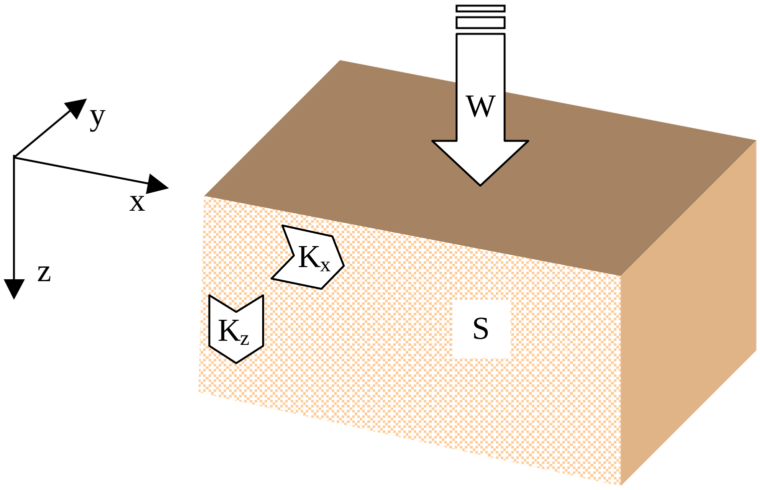


Figure 3.9: Components of Darcy's equation

If hydraulic conductivities can be estimated and starting values assigned for the hydraulic heads across the catchment, the directions and volumes of water flow through the bedrock can be computed. MODFLOW can determine water output to streams from groundwater baseflow, and can respond to recharge from rainfall events. River water can also be gained into groundwater storage where river channels cross unsaturated bedrock. Use of the MODFLOW package will be discussed in section 3.4.

A further component that is necessary for hydrological modelling is the simulation of surface water flows within the streams and rivers which make up the drainage system of the catchment. Many hydrological models have a river routing component in addition to hillslope runoff simulation, but again it was decided to use separate specialist packages for this aspect of the Mawddach project. Experiments have been carried out with the river routing packages HEC1 and GSTARS.

River channels of widely differing character make up the Mawddach system (fig.3.10). Flows occur under a mixture of critical and subcritical regimes, necessitating the modelling of varying water velocity-depth relations within individual reaches.

Figure 3.10: The River Mawddach in Coed Y Brenin, showing a transition from fast shallow supercritical flow in the middle distance, to slow deep sub-critical flow in the foreground.

For a given rate of river flow, it is possible that water may move downstream as either a deep slow moving body (sub-critical flow) or as a shallow fast moving body (super-critical flow). The nature of the flow will be determined by the bed slope and channel frictional resistance. A change from sub-critical to super-critical flow may inhibit the overall river flow, since frictional forces play a greater retarding role in shallow channels with fast moving water. It is also important to know which flow regime is operating if sediment transport modelling is to be carried out. Sediment may be readily transported through super-critical reaches but be redeposited in sub-critical reaches of the river.

The software package GSTARS (Generalized Stream Tube model for Alluvial River Simulation) produced by the US Bureau of Reclamation (Yang and Simões, 2000) has proved successful in handling mixed flow regimes. This program can be described as a one-and- a-half dimensional model, since river flow is determined from a finite number of specified cross sections (fig.3.11).

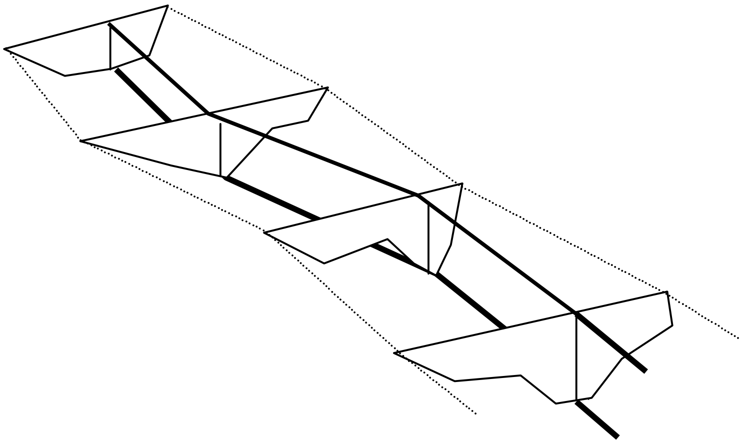


Figure 3.11:
Schematic representation of the GSTARS model, with river flows determined from channel cross sections and river bed elevations at specified points

The river routing functions of HEC-1 and GSTARS are intended for modelling flows at discrete points along a river channel, so do not have the facility to map the extent of overbank flooding onto the floodplain area during storm events.

It was considered essential to predict overbank flood extent as an element of the flood prediction system for the Mawddach. To accomplish this, experiments have been carried out with the programs River2D (Steffler and Blackburn, 2002), and RMA2 (King et al.,1997) within the Surface Water Modelling System package. Both are finite element models which allow the channel and floodplain topography to be entered as an irregular triangulated grid (fig.3.12). The approach used by the programs is similar, employing the Navier-Stokes equation for turbulent flows, bed friction with Manning's equation, and eddy viscosity coefficients to define turbulence.

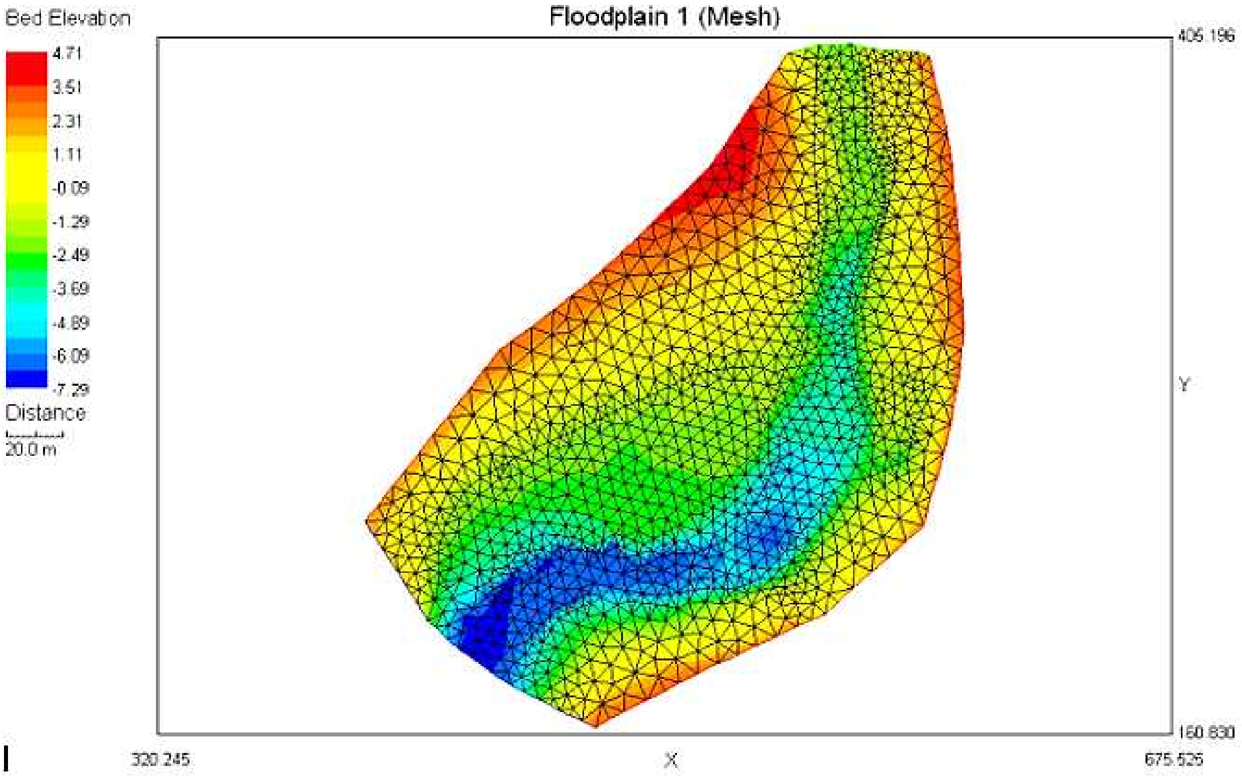


Figure 3.12: Finite element grid for the Mawddach floodplain at Tyddyn Gwladys, Coed y Brenin, developed with River2D

When simulating flood events, the software must be able to handle the wetting of additional surface elements as the water surface extends beyond the river banks and onto the flood plain. Changes to the boundary geometry of the river channel were found to produce mathematical instability in some RMA2 models, causing the model to fail without a solution. The River2D modelling code has a mechanism to link river levels to the groundwater profiles below adjacent hillslopes, and this has proved to produce more stable results.

The governing equation for the RIVER-2D program is the conservation of water mass:

$$\frac{\partial H}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0$$

where the term in H refers to the rate of change in hydraulic head as river level changes, and the terms in q are the discharge gradients in the coordinate directions x and y.

Beyond the channel margins, this equation is replaced by a groundwater equation

$$\frac{\partial H}{\partial t}=\frac{T}{S}\left(\frac{\partial^2}{\partial x^2}(H+z_b)+\frac{\partial^2}{\partial y^2}(H+z_b)\right)$$

in which T is transmissivity, a measure of the rate at which water can permeate through the geological formation, S is the storativity which determines the volume of water which can be held within a unit volume of the rock material, and zb is the ground surface elevation. Due to its mathematical stability, River2D is the preferred software option for modelling overbank flooding. Although intended for modelling river reaches of limited extent, River2D has also proved effective in modelling tidal flows within the Mawddach estuary.

An additional aspect of interest for the Mawddach river system is the movement of sediment during flood events, leading to accumulation around the town of Dolgellau and the head of the Mawddach estuary. Two software packages, GSTARS and CAESAR (Coulthard, 1999) for modelling sediment movement are discussed in section 3.3.

Summary

- The main components of a conceptual hydrological model for storm events in the Mawddach catchment are: surface runoff, lateral flow at shallow depth, transfer between surface water and groundwater stores, and river routing.
- Models will be required for hillslope hydrological processes, river routing and flow onto floodplains. Additionally, sediment transport during flood events is of importance to the study.
- Lumped parameter models are capable of predicting river discharge for different intensities and duration of storm rainfall. However, these models would not be adequate for modelling the areal extent of flooding within the catchment, and would be unsuitable for predictive studies which model changes in land use.
- The Kirkby topographic index can provide an effective way of predicting soil moisture content and the locations of surface runoff by using a digital elevation model for the catchment.
- Distributed models, in which hydrological parameters are specified for grid points across the catchment, provide a means of relating the mathematical model directly to aspects of topography, soil type and vegetation. The grid spacing possible for a distributed model will depend on the available computing capacity.
- Simple hillslope runoff-infiltration models will not adequately represent the short term storage and release of groundwater which occurs during and after storm events. Incorporation of a groundwater model may be necessary for adequate representation of flood processes.
- River routing within the Mawddach catchment must take account of variations in flow regimes of mountain streams.
- A floodplain model must be able to represent the changing boundary of the river channel as water spills over the river banks during flood events. This requires a stable system of differential equations within a finite element model.